Parylene-membrane Piezoresistive Pressure Sensors with XeF_2-etched Cavity

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Abstract— **Pressure sensors have been fabricated based on a deformable parylene C membrane over a cavity etched in silicon. The cavity is obtained by XeF_2 etching, using a parylene mask composed of an array of holes. A subsequent parylene deposition fills the holes, thus sealing the cavity and completing the membrane. Gold piezoresistors are used to sense the membrane deformation.**

Compared to traditional pressure sensor designs, this process is more easily integrated into other processes, as no double-side machining or wet silicon etching is needed.

The use of parylene is advantageous under certain points of view. First, it protects the piezoresistors and silicon, due to its well known barrier and chemical inertness properties. Second, contrary to other materials commonly used to fabricate pressure sensor membranes (e.g., polysilicon, silicon nitride), parylene is flexible, and thus more resistant to shocks. These two reasons make the sensor useful in chemically and physically harsh environments.

I. Introduction

Pressure sensors have been one of the first and most successful applications of MEMS technology, and they account for a large part of the MEMS market. It is estimated that the market for MEMS pressure sensors in 2006 has been 1.2 billion dollars [1], with numerous applications in the automotive and biomedical field.

The most common MEMS pressure sensors are based on a silicon diaphragm, typically fabricated by anisotropic wet etching [2]. This normally requires double-side wafer processing. Other sensors are fabricated by surface micromachining, using polysilicon or silicon nitride as membrane materials [3].

Micromachined pressure sensors based on polymers are not common. A spiral-tube device, which mimics a technique used in macroscale sensors, has been fabricated using parylene [4]. Parylene has also been employed in capacitive pressure sensors [5].

The sensors presented in this paper feature a parylene membrane, with metal strain gauges as sensing elements. The authors were not able to find an example of such devices in the liturature. On the one hand, parylene has properties desirable for a pressure sensor membrane, in particular flexibility and chemical inertness. On the other hand, parylene shows limitations typical of polymers, such as relatively high permeability to gases compared to materials like silicon or silicon nitride. In addition to that, a parylene-based sensor should only be operated below the glass transition temperature of the polymer, which is in the 80 - 120 °C range for parylene C.

II. Device Design

The sensors were designed to satisfy a number of constraints: single-side process, measurable pressure at least in the 150-200 psi range, only parylene as a structural material (on silicon substrate), simple metal strain gauges as sensing elements, small size and limited amount of silicon removed. These constraints arise from the application these pressure sensors are mainly designed for, i.e. integration into electrolysis-based parylene balloon actuators for movable neural probes [6]. The sensors are designed to be placed inside the electrolysis chamber, where the pressure generated by the electrolysis gas-phase products needs to be monitored.

The sensors are based on a square parylene membrane over a cavity etched into silicon. Silicon is etched beneath the membrane by XeF_2, through an array of holes patterned on the parylene itself (parylene is a good masking material for XeF_2). XeF_2 etches silicon isotropically, so the etching starts by forming a spherical cavity under each hole. If the etching is carried on deeper than half the distance between the holes, the etched spherical cavities merge and a larger cavity is formed (refer to the fabrication steps in Fig. 1). The cavity is then sealed by a subsequent parylene deposition [7].

The shape of the cavity is determined by parylene-filled trenches, which act as etch stops for XeF_2 etching. The etch stops also set a limit on the maximum cavity depth. Similar trenches are used to anchor the parylene membrane around the cavity. When pressure is applied to the membrane, tangential stress at the parylene-silicon interface ensues. Even though the use of a promoter already improves the adhesion between the two, the use of anchors for parylene enhances the reliability.

The deformation of the membrane is sensed by four metal strain gauges embedded in the parylene membrane. These are placed at the four edges of the membrane and arranged in a Wheatstone bridge configuration, in order for common-mode effects on resistance to cancel out. The arrangement is shown in Fig. 2: when the membrane is deformed, the gauges on the right and left side of the membrane experience a decrease their resistance, while the ones on the top and bottom side experience an increase in resistance. The strain gauges cannot be placed exactly at the edge of the cavity due to the presence

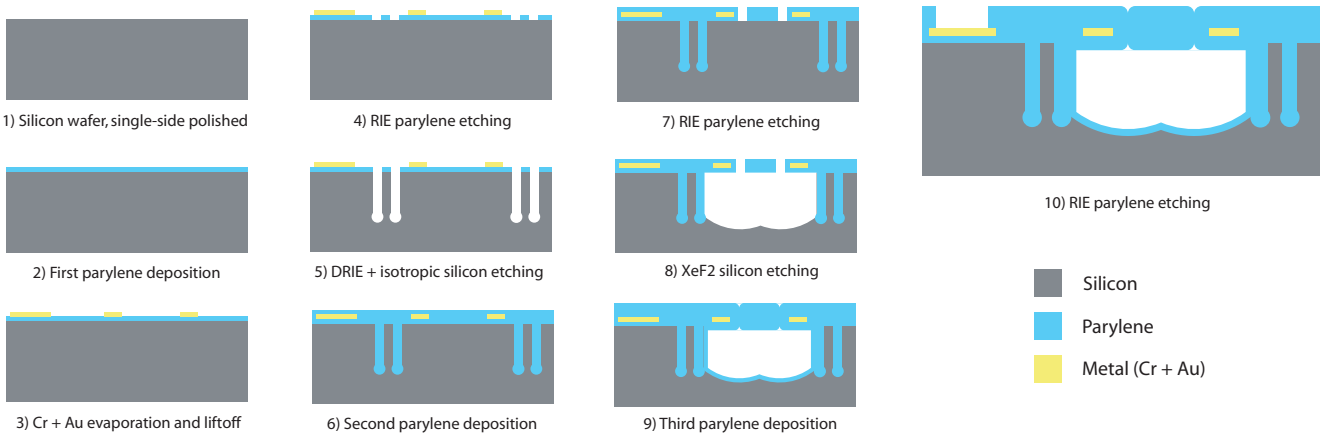


Fig. 1. Process flow for the fabrication of the pressure sensors.

of the etch stops. Also, the gold traces need to be routed across the boundary of the cavity, and therefore some interruptions in the etch stops are required.

Sensors with different cavity dimensions were fabricated, ranging from 100 μm x 100 μm to 200 μm x 200 μm. The total membrane thickness is 21.5 μm, as explained in the next section. A finite element simulation of the membrane shows that the deformation at the center of the membrane is 8.5 nm/psi for the 200 μm x 200 μm case.

III. Fabrication

The process steps are illustrated in Fig. 1. The prime wafer is first cleaned in piranha solution for 10 minutes. Adhesion promoter for parylene-silicon adhesion is then applied by leaving the wafer for 2 hours in a solution of deionized water, isopropyl alcohol and A-174 (from Specialty Coating Systems) in 50:50:0.5 proportion. A thin layer of parylene, 0.8 μm thick, is then deposited.

Gold is thermally evaporated on the parylene layer, using chrome as an adhesion layer (1000 Å Au on 100 Å Cr). The first layer of parylene is needed as a support for the piezoresistors. As a result, the metal traces are completely enclosed in parylene.

Parylene is patterned by reactive ion etching (RIE) in O_2 plasma, in order to expose silicon in the areas designated for the anchors and XeF_2 etch stops. Both are etched at the same time by deep reactive ion etching (Bosch process). A final SF_6 isotropic etch creates a larger cavity at the bottom of the trench, improving the anchoring ability [8]. The trenches are 7.5 μm wide and 40 μm deep. A second parylene layer is deposited, 8.5 μm thick, enough to fill the trenches and get sufficient planarization.

The hole array for XeF_2 etching is then patterned. The holes are 7.5 μm in diameter. An aluminum layer is first deposited by thermal evaporation. The thickness of the layer is 4000 Å, sufficient to ensure coverage also over the anchors and etch stops, where the parylene is not flat. This layer acts as a mask for parylene patterning and it allows lithography with a 2-μm photoresist layer, much thinner compared to the 10 μm layer that would be needed to etch parylene with a photoresist mask. Thin photoresist is desirable for accurate patterning of such small holes. After aluminum patterning by wet etching, parylene is etched by reactive ion etching in O_2 plasma. The aluminum mask is then removed.

Before XeF_2 etching, a dip in BHF or 5% diluted HF is mandatory to ensure the thin surface native oxide is removed from silicon. Without this, XeF_2 etching proceeds very non-uniformly from hole to hole. XeF_2 etching is performed in pulsed mode [9]. Due to the transparency of parylene, it is possible to observe the progress of the etching.

A third parylene layer is then deposited, 8.5 μm thick. The conformal nature of parylene deposition makes it possible to seal the cavity. A final parylene RIE etch with 20 μm thick photoresist mask is used to open the pads for external connections.

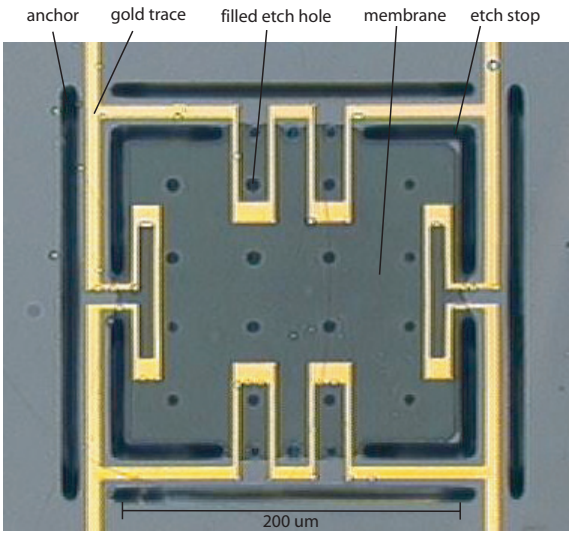
From the process data, the total parylene membrane thickness is estimated to be about 21.5 μm, which is the sum of all the depositions above, to which the etching hole radius needs to be added, due to parylene being deposited also on the bottom surface of the membrane during sealing.
Because of the limited thickness of the first parylene deposition, the gold traces are close to the bottom surface of the membrane, with positive effects on the sensitivity.

Optical microscope pictures of two fabricated devices are shown in Fig. 2.

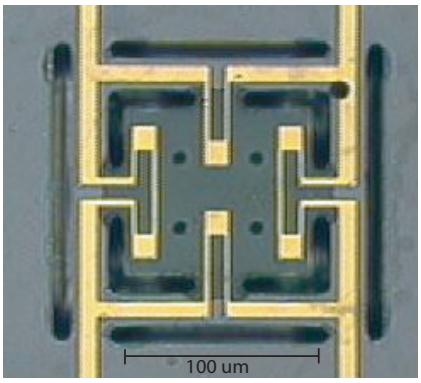
IV. Results

A. Pressure Response

To measure the pressure response, the sensors were placed in a pressure chamber connected to a N_2 cylinder through a pressure regulator. The chamber is equipped with feed-through wires. Fig. 3 shows the response of a 200 μm x 200 μm sensor up to 200 psig. The response deviates from linearity and it is better interpolated by a quadratic function. The signal at 0 psig can be recovered after the experiment, implying that no plastic deformation occurred.



(a) 200 μm x 200 μm cavity



(b) 100 μm x 100 μm cavity

Fig. 2. Top-view of two fabricated devices of different dimensions. The cavity under the silicon can be clearly seen (dark grey) together with the hole array for XeF_2 etching (black dots over the cavity). The cavity is surrounded by the etch stops and anchors (black).

B. Parylene Permeability

The effect of gas permeation through parylene was tested by exposing a sensor to constant external pressure. Permeation causes gas to accumulate into the sealed cavity, and the pressure inside the cavity increases until it reaches the value of the external pressure. As a consequence, the differential pressure on the membrane decreases over time. If the external pressure is then released, the pressure inside the cavity will be higher than the external pressure. Gas will thus gradually permeate out of the cavity, until the pressure inside and the pressure outside are again equalized.

This behavior is modeled. $P_e(t)$ and $P_c(t)$ are the external and cavity pressure respectively, μ is the permeability coefficient of parylene to some gas (N_2 in this case), b is the membrane thickness, A is the membrane area, h is the cavity depth (the cavity is assumed to have a flat bottom, neglecting the pattern left by XeF_2 etching). The variation in the number

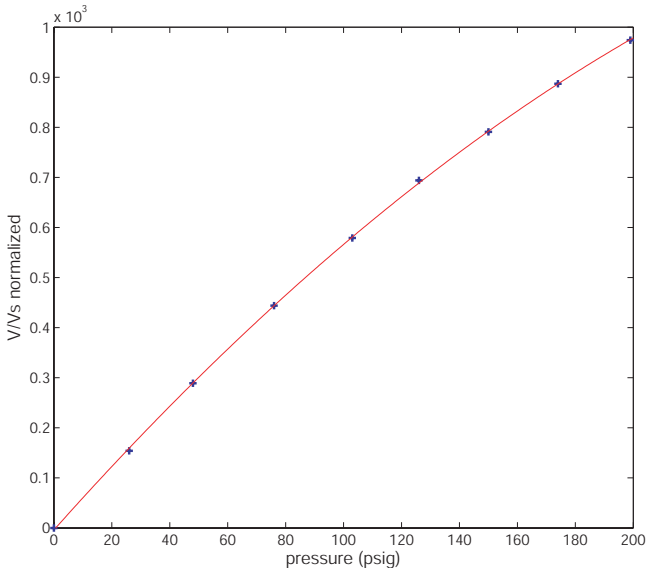


Fig. 3. Pressure response of the 200 μm x 200 μm sensor. V/Vs is the ratio of the bridge output voltage and the supply voltage. The data point at atmospheric pressure (origin of the plot) is taken as a reference for the data, to eliminate the bridge offset. The data points are fitted to a quadratic function.

of gas moles inside the cavity n_c can be written as

$$\frac{dn_c}{dt} = \mu \frac{A}{b} [P_e(t) - P_c(t)]$$

We assume that the deformation of the membrane causes negligible change in the volume of the cavity, so its value is fixed at $V = Ah$. By applying the ideal gas law (temperature is assumed constant), we obtain a differential equation relating $P_c(t)$ to $P_e(t)$

$$\frac{dP_c}{dt} = \mu \frac{RT}{hb} [P_e(t) - P_c(t)]$$

where R is the ideal gas constant and T is the temperature. Given the form of the equation, we can regard the term $\tau = hb/(\mu RT)$ as the time constant of the system.

Fig. 4 shows the results of the test on a 200 μm x 200 μm sensor. Initially the sensor was left for more than a week at atmospheric pressure, so that the initial pressure inside the cavity became equal to atmospheric pressure. The sensor was then exposed to a pressure of 100 psig in N_2 environment, at a temperature of 22°C.

The value for the time constant can be extracted from the experimental curve, and it is found to be τ = 85 hours. From the time constant, we can find the experimental value for the permeability coefficient. A correction is applied to take into account that 15% of the membrane area is covered by metal, whose permeability is negligible compared to parylene's. With this information, we find $\mu = 4.7 \cdot 10^{-15}$ mol/(m·hour·Pa). This can be compared to a value of $6.79 \cdot 10^{-15}$ mol/(m·hour·Pa) reported by our parylene supplier (Specialty Coating Systems), measured at 25°C following the ASTM D 1434 standard. A possible explanation for the lower permeability measured is the annealing of parylene during fabrication. During the

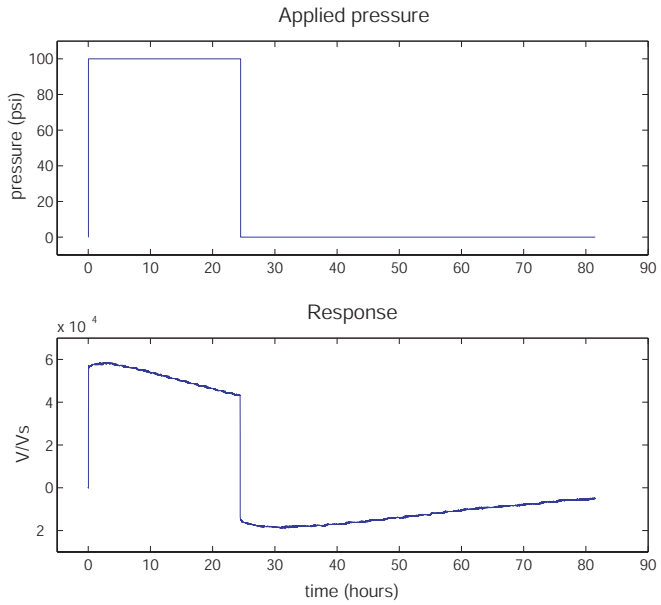


Fig. 4. Effect of permeation of N_2 through parylene on pressure response of the 200 μm x 200 μm sensor. V/Vs is the ratio of the bridge output voltage and the supply voltage. The initial data point (at atmospheric pressure) is taken as a reference for the data. Only part of the relaxation after pressure release is shown.

process, photoresist has to be baked at 100 °C or 120 °C for periods ranging from half an hour to several hours, and the parylene already deposited on the wafer is subject to the same thermal treatment. A decrease in permeability after parylene C annealing has been reported in the literature [10], [11].

Techniques are available to drastically reduce the permeability of a parylene film. As reported in [12], a thin aluminum layer (1000 Å) can be used to reduce the permeability by about 5 orders of magnitude.

If allowed by the application, a channel can be used to connect the cavity to a reference pressure. The channel can be obtained under the parylene by the same XeF_2 etching technique.

V. Conclusion

Pressure sensors based on a parylene membrane with gold strain gauges have been designed, fabricated and tested. The fabrication steps require only one-side wafer processing and avoid the use of anisotropic wet silicon etching. This makes the process more easily integrable into other processes.

The flexibility of parylene makes the membrane more resistant to mechanical shocks compared to brittle materials like silicon or silicon nitride, and its chemical inertness makes it possible to place the sensor in contact with chemically reactive media. Another advantage of parylene is its biocompatibility.

Parylene exhibits relatively high permeability to gases, which causes drifts in the measured pressure. Also, the temperature range in which the pressure sensor can operate is limited by the glass transition temperature of parylene.

Other polymers can be used to fabricate the membrane. Attention must be paid to their properties, for example their creep and permeability characteristics, which can cause drifts in the measurements. Moreover, a conformal deposition of the polymer must be possible, in order to seal the cavity.

By exploiting the drift in the sensed pressure, this device can also be used for a rough estimation of the polymer permeability. The main sources of inaccuracy are the imperfect knowledge of the cavity volume, the non-uniform thickness of the membrane (due to the filled holes), and the fact that the polymer undergoes processing that may alter its properties.

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